CAMERA ARM SYSTEM FOR DISASTER RESPONSE ROBOTS SPACE-EFFECTIVE DESIGN AND PERFORMANCE EVALUATIONS OF PROTOTYPE DEVELOPMENT

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In this paper, design and development strategies of a camera arm system for disaster survey robots are discussed. Unlike the previously-provided system, which has been used repeatedly for information gathering purpose at the FUKUSHIMA nuclear disaster in 2011, a newly developed camera arm is mounted on a crawler-type remote operation robot, Sakura II, to enhance image-based investigating performance in human-inaccessible regions. A wide variety of machine design aspects for practical uses of a camera arm system, including functional requirements, space-effective realizations and experimental evaluations, are discussed.

Keywords:
disaster response robot, rescue robot, remote operation robot, rescue engineering, camera arm, collision protection

1. Introduction

A newly developed camera arm system mounted on a remoteoperation robot for disaster-site survey is presented. The Great East-Japan Earthquake in 2011 has caused a serious nuclear disaster at FUKUSHIMA in Japan. For information-gathering purpose, our remote operation robot,Quincespecialized for this disaster [Koyanagi2013], has been used frequently at the high-radiation inside of the collapsed reactor buildings [TEPCO2014]. PackBot [Trainer 2014][Yamauchi 2004], one of the most reliable remote operation robotsmade by iRobot corporation, was first deployed into the reactor buildings. However, the narrow, steep and watery stairs prevented its approach to upper floors [Tadokoro 2012]. Quince with higher traversing abilitywas then sent to the disaster site. While system customizations has been repeated according to mission objectives [Yoshida 2014], Quince has achieved unmanned survey missions including the top floor many times. A numerous high-resolution pictures, e.g. Fig. 1 [TEPCO 2011][TEPCO 2012], provided us the significantinformation useful for the reduction of on-site worker's radiation exposure as well as for the reactivation of the spray cooling system [Nagatani 2013], leading to the cold stop state of the nuclear reactors.

Figure 1. Pictures taken by Quince via remotely operated image-based investigation inside the reactor building at the FUKUSHIMA nuclear disaster in 2011

In the subsequent project under NEDO Research and Development Project for an Unmanned Disaster Response System (FY2011- FY2012), in order to enhance further the robot information-gathering ability, a disaster survey robot system, named Sakura II, has been developed as in Fig. 2 and Tab. 1.In addition to fundamental improvements of dust and water proofand payload-carrying capability, a camera arm system is newly developed and mounted. Unlike the previously-provided Quince system, where the camera unit is rigidly fixed to the robot body without arms, the versatility of movable camera position and orientation are offered together with the ability of light-work gripper operations. In this paper, its camera arm system is focused, and from the view point of machine design engineering, its target performance, space-effective realization and performance evaluations are fully discussed [Toda 2014][Yamato2014].

Figure 2. Camera arm systemon disaster response robot (Sakura II)

Mounting	on disaster response robots
Equipment	wide/high resolution camera, lights, gripper
Functions	posture holding without power consumption collision protections dust and water proof (corresponding to IP67) absolute joint angle sensing (all joints)
Structure	0.6m x 3 links (changeable), 8 joints
Camera	2.3m (maximum height from the floor)
Work	4.5kg (depending on link extensions)
Camera Joint	pan and tilt axes (continuous rotation available at pan axis)
Gripper Joint	grasping/wrist rotating axes (continuous rotation available at wrist axis)
Weight	16kg: arms, 4kg: base and connecting plates
Connection	power: 30V, communications: CAN, Ethernet

Table 1. Basic specification of camera arm system

In terms of mobile manipulators, extensive effortscan be found in the literature, in which primary issues are on kinematical or dynamical studies rather than real-world uses.Among those, a robot system known to be practically reliableis a HELIOS series[Hodoshima 2011], where similar to our system, a gripper arm with small camera is on a crawler type robot. But the primary objective in their arm useis fundamentally different from the objective of our system.It is used at the start of step climbing to lift up the robot body and the necessity of subcrawlers is eliminated. From the experience of the Quince missions mentioned above, we consider the role of a camera view to be extremely significant for unmanned missions, and the traversing performance must be ensured independently from the camera arm role. In [Tsumaki 2012], although the remote operability is included in its target specifications, cameras cannot be seen in the presented drawings and robot pictures, and besides, dust and water proof is not pursued.PackBot [Trainer 2014]is asuccessful robot usable in difficultenvironments. Unfortunately, any of its internal structures are not known, typical to military-use products (note that its configuration of crawlers as well as flipper arms are different from Sakura II in Fig. 2, and in fact,PackBot could not climb to the upper floor at the reactor buildingright after the earthquake[Tadokoro 2012]). In KOHGA [Kamegawa 2004], the importance of camera systems is discussed, but double-head snake-like robot focusesnear-floor investigations, and close inspections at overhead locations are often required as we experienced.

2. Performancerequirements

For camera arm systems, 1) without deteriorating the traversing ability of crawler robots, it is required to be capable of 2) investigating environments through clear imagesincluding overhead locationsor narrow tight spacesand 3) performinglight-worktasks such as sampling, debris removing and door opening. Furthermore, various functional requirements involved by remote operations in unknown disaster sites, must be considered.The targetperformance specified in this project is summarized below:

1. Traversing ability of disaster response robots
- Not deteriorating the traversing ability. Typically traversing on unknown irregular fields including 45-degree stair climbing is required.
- Folding entire camera arm systems, so that it can be included inside the crawler robot footprint with allowable gravity center location to avoid destabilization in traversing on irregular terrains or climbing stairs as well as to perform point-turn motion at narrow space.

2. Enhancement of information-gathering ability
- Equipping with a movable high-resolution camera and alighting unitfor dark-space investigations.
- Enabling versatile positions and orientationsof camera unit for high-position and narrow-spacesurveys such as ducting pipes arranged at ceiling.

3. Light-work operation ability
- Equipping with a gripper to operate remotely light-work taskssuch as sampling, debris removing and door opening.

4. Power consumption
- Holding the pose of camera arm without wasting battery power (in remotely-operated investigation,considerable long time is expected to be of staying at restas compared with the time of moving).
- Switching remotely lights, motor drivers and othercircuit boards to reduce power consumption.

5. Collision protection
- Offering collision protection functions for stress-free and successful operations in unknown narrow tight spaces or easily balance-losing fields.

6. Dust and water proof
- Allowing unrestricted operationseven in dusty or water-sprinkled fields typical of disaster sites.
- Prohibiting, in particular, any exposures of electrical components to the outside atmosphere.

7. Alleviation of operator stress
- Maximizing joint angle ranges, or providing continuous rotations if applicable.
- Sensing absolute angles for all joints.
- Switching remotely localcontroller function as active or passiveaspreferred by operators.

3. Mechanical design

The design strategy to meet the above requirements is discussed here. Configuration of the arm system and its joint components are shown in Fig. 3and Tab.2.

3.1 Link structure and component design

To allow wide-ranging camera positions and orientations, it is strongly desired to configure arm structure as long as possible with appropriate joint assignments. For this purpose, it is structured by three links with the camera and light unit at its head, and each link length is maximized but possible to be included inside the crawler robot footprintby folding(0.6m each), so that the camera position can reach to overhead positions as well as the robot can make a point-turn at narrow spaces. Besides, at the end of the 2ndlink, two-joint gripperis installed for light-work operations. The shape of the 3rd(most upper) link is bended aboveto locate the camera on an applicable position for remote operations of gripper tasks and crawler robot movements. Three elevation link structure is formed on a yaw joint at the arm base. Each joint angle range is maximized with absolute angle sensing. In particular, the base yaw axis is able to rotate in [-270 +270] degree with mechanical limiters.Three link frames will be composed by light and tough carbon pipes connected through duralumin-made joint units, where the 1st and 2nd pipes can be easily changed to a different length (shorter) link if necessary.

Arm posture holding

To prolong the limited energy source, nonbackdrivable gear or electromagnetic motor brake will be adopted, so that the arm posture can be kept without consumingadditional electric power. Associated also with the remote switching feature of active or passive joint control, the selection of posture-holding means for each joint, either worm gear or brake, is indicated in Tab. 2.It is important to note that with this design policy, thermal time restriction of motors and motordrivers can be significantly facilitated. Mainly, torque constant of motors and maximum current of motor drivers should be focused in the component design process.

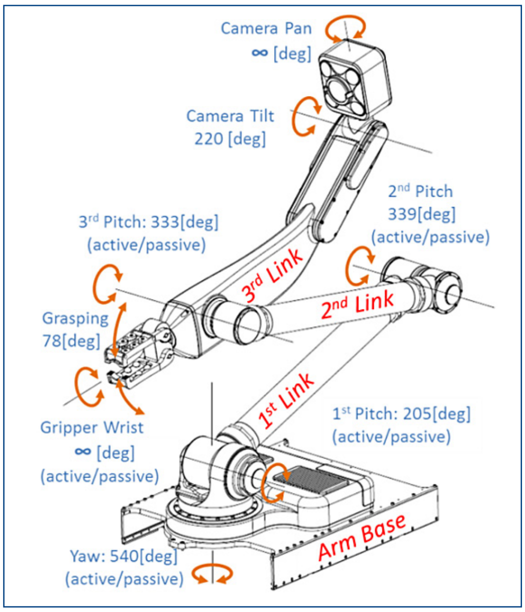

Figure 3. *Link structure and joint assignment*

Joint Axis	Torque	Gear Ratio	Posture Holding	Collision Protection
Yaw Axis at base	30mNm/A	405	Electromagnetic Motor Brake	Friction Coupling
Pitch Axis at Base	60mNm/A	480	Electromagnetic Motor Brake	Friction Coupling
Pitch Axis at Elbow	38mNm/A	480	Electromagnetic Motor Brake	Friction Coupling
Pitch Axis at Gripper	30mNm/A	540	Electromagnetic Motor Brake	Friction Coupling
Rotating Axis at Gripper	30mNm/A	162	Electromagnetic Motor Brake	None
Grasping Axis at Gripper	15mNm/A	870	Worm Gear	Friction Clamping
Tilt Axis at Camera	15mNm/A	270	Worm Gear	Friction Belt
Pan Axis at Camera	15mNm/A	270	Worm Gear	Friction Belt

Table 2. *Joint component design*

Active or passive switching of joint controls

For all the backdrivable joints, remote switching features of active or passive control should be allowed to promote the operability of the arm system. This can be provided through local joint controllers.

Friction coupling for collision protections

In order to avoid the destruction due to collisions as much as possible, frictional dissipations of impulsive-force energy is implemented at several parts through simple clamps, friction belts and built-in joint torque limiters, where intentional slipping will occur for pre-assumed excessive external forces.

Dust and water proof and system independence

In order to promote dust and water proof property and to reduce the dependence to other robot systems,all the necessary electrical components, such as power supply circuits, motor controllers or wireless connection units,must be arranged inside the arm body while only power supply and communication cables (CAN, Ethernet) are allowed via water proof connection to the crawler robot.

Camera model

The quality of camera images is the most important element for image-based inspection missions. The camera unit selected here(Axis Communications AB) is exactly same as the one used at the actual nuclear disaster missions asshown in Fig. 1. Although it is heavy to be attached at the arm tip, the resolution and the clearness have been found to be appropriate through the actual missions [TEPCO 2014].

3.2 Camera and light unit

Two orthogonal joints of pan and tilt axes for maneuveringthe camera direction should be provided with their absolute joint angle sensing. In particular, for look-around 360-degree views to be available, continuous rotation of the pan jointis strongly demanded. Ensuring the consistency of the space-effective arrangement and the functionality realization has been a primary issue of this joint design, i.e., twopan and tilt axes joints must be configured 1) compactly at the narrow bar-like space of the arm tip with the functions of 2) the collision protection, 3) the posture holding without consuming motor currents, 4) the absolute angle sensing, and 5) the dust and water proof.

3.2.1 Space-effective design of joint mechanics with collision protection and posture holding functions

In this project, a differential mechanism by three bevel gears is applied for the compact configuration of two orthogonal joints as shown in Fig. 4. Then, pairs of friction belts and worm gears are space-effectively arranged for driving-force transfers, collision protections as well as no-motor-current posture holdings. Besides, adjustment mechanisms of belt tensions are installed to ensure successful slipping between the differential mechanism and the worm gear whenever collision occurs.

Even in the case of the slipping, the absolute angles of two joints can be effectively measured by connecting absolute angle sensors appropriately to the differential mechanism. It should be noted that a slip-ring is installedinternally at the pan axis, allowing its continuous rotations.

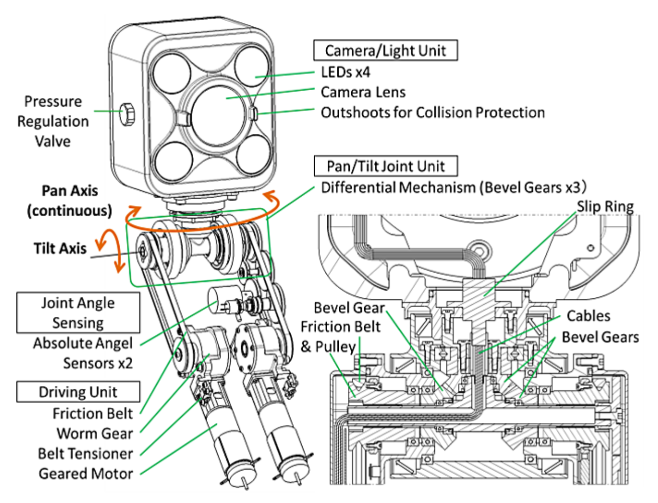

Figure 4. *Joint structure of camera and light unit*

3.2.2 Camera head design with impulsive-force resistance and heat dissipation

The camera unit, located at the arm tip, is most likely to have collisions to surroundings. Moreover, due to the necessity of high illumination, this will be the most heated part in the arm structure (rather than motor circuits). Thus, 1) dust and water proof, 2) shock resistance and 3) effective heat dissipation must be in consideration. To meet these requirements, an approach of packing all the necessary electrical components by metal materials is adopted, providing suitable features for waterproof sealing, impulsive-force resistance and thermal conduction.

The heat reducing and releasing must be taken into full account as mentioned before. Here, the lighting, or heating, source is divided into four LED lights, and current supply for each LED circuit is regulated by a current controller. While the total brightness is sufficiently achieved by four LEDs, the produced heat can be physically distributed suitable for its dissipation through the metal housing. Note that a pressure regulation valve is also prepared on it to avoid the sealing deterioration due to dramatic change of the internal pressure through water cooling.

3.3 Gripper unit

As for the applicability to various uses, two joint axes of gripping and endless wrist rotating with absolute angle sensing are considered.A primary difficulty for the gripper unit design is then caused by the fact that while the wrist joint is preferred to be able to rotate endlessly, the griping joint must be placed beyond this continuously rotating joint, and both of absolute angles should be measured.

3.3.1 *Gripper joint design with continuous rotation and absolute angle sensing*

The devised mechanism in this project is shown in Fig. 5.In this design, a worm gear is used for symmetric compact drive of fingers, and its drive shaft (worm gearshaft)is arranged in the identical line with the hollow wrist rotating shaft. The interference between two joint axes can be removed by local position controllers if each absolute angle can be obtained independently.

The absolute angle information for the gripper opening motion, in fact, corresponds to the relative angle of the worm gear shaft with respect to the wrist-rotating shaft. To extract this relative angle, the differential property of planetary gear system is tactfully used, where the sun gear is embedded on the worm gear shaft and the outer gear is rigidly fixed on the wrist rotating shaft, associating the career angle relative to the link frame with the absolute angle information of the gripper opening and closing.Note that the absolute angle of the wrist rotation can be easily gained by an absolute sensor mounted on the link frameby a usual manner.

The gripper is another likely part of collisions with external objects. To protect its gear train from possible impulse and to offer stress-free operations, an adjustable friction clamping is applied to fix the fingers to worm wheel shafts.

3.3.2 *Advantages in this design approach*

In this design way, several advantages can be taken such that1) the endless wrist rotation is available, 2) the absolute angle information of each joint is obtained,and 3) all the electrical elements, which require the connecting cables for power suppliesand information transfers, can be arranged in the space not beyond the moving part, suitable to sealing design for dust and water proof.

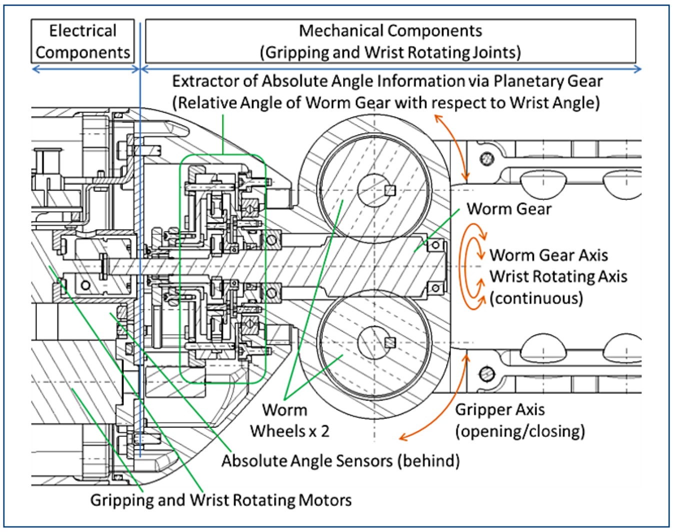

Figure 5. *Internal structure of gripper joint*

3.4 *Pitch joint*

High mechanical robustness of the camera arm system is significantly important to operate real-world missions. For pitch joints having the role of elevations of the camera and the gripper, there are several required functions of 1) transferring relatively large torques, 2) passing electrical cables through joints, 3) holding the arm posture without motor current consumptions, 4) protecting gears and other mechanics from impulsive forces, and 5) sensing absolute joint angles.

3.4.1 *Pitch joint configuration*

As a representative example, the 2nd pitch joint of the system is taken, and its cross-section diagram is shown in Fig. 6. Right half of the diagram indicates the 1st link side, and left half shows the 2nd link side. A motor with an electromagnetic brake in the 1st link is at the back side of the figure, where the axis of the motor is perpendicular to the joint shaft, and the motor torque is transmitted to the 2nd link through a bevel gear, a harmonic drive and a torque limiter aligned along the joint axis.

3.4.2 Collision protection mechanism

Without torque limiter, impact forces applied by collision can directly act to gear teeth of the harmonic drive. To protect the mechanics, a friction-type torque limiter is installed at the output of the harmonic drive. As shown in Fig. 6, a flange fixed to the 2nd link is sandwiched by two friction plates. These flange and two friction plates are tightened onto the output of the harmonic drive by a large diameter nut through disc springs. As verified in the experiment later, the slip torque can be adequately adjusted by tightening the nut that can be easily accessed by removing detachable cap of the joint. Note that electromagnetic brake installed on the motor axis realizes the non-power-supplied posture holding of the arm to enlarge the operation time.

3.4.3 *Thin pipe for absolute angle sensing and wire harness protection*

We select a hollow structure for the main joint drive shaft consisting of bevel gears, harmonic drives and torque limiters. A merit of wire harnesses passing through the hollow joint shaft is that there is no exposure of wiring to the external atmosphere. Furthermore, wire bending due to the joint rotation is minimized by putting them through the exact center of the joint axis. The reliability of electrical components and their dust and waterproof properties are promoted by this design.

At the time of collision, joints can be moved without motor rotations by slips of torque limiters. If absolute angles of joints are not obtained in such a case, an undesirable initializing process of the arm posture is required. Therefore, we devise a particular arrangement of angle sensors for obtaining absolute joint angles. A thin pipe, fixed on the 2nd link and passed through the main hollow shaft, is used to deliver directly and mechanically the rotation angle of the 2nd link to the 1st link, where an absolute angle sensor is mounted on. Another important role of the thin pipe is that it works as a mechanical guide for wire harnesses passing through the joint shaft.

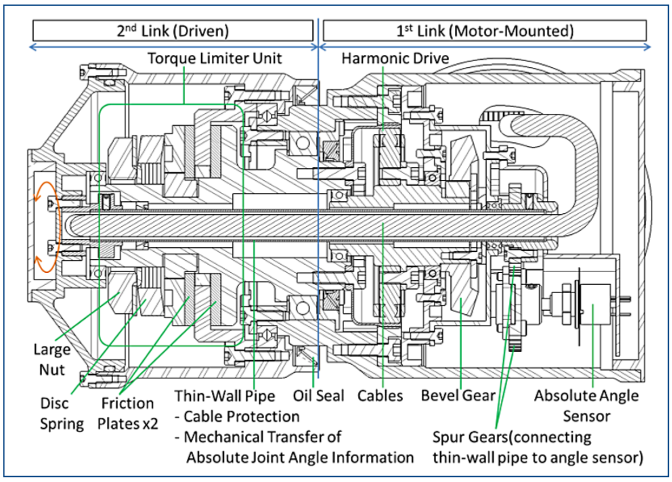

Figure 6. *Internal structure of elbow pitch joint*

4. Performance evaluations

The evaluation results are discussed in this section.

4.1 *Dust and water proof*

The water proof ability has been evaluatedby actually immersing the arm into 0.5m depth of waterat 17degree of temperature as shown in Fig. 7, where all the joints have been kept movingexternally during a half hour of the testing.Before this evaluation, a number of wet detecting stickers were put on the internal walls. It was then confirmed that all the faces of both moving and not-moving parts were effectively sealed against the water pressure.

4.2 Heat dissipations

The effectiveness of the sealing, in general, can bea detrimental factor regarding thermal dissipation. The amount of heat produced by electric circuits must be balanced always with heat dissipation ability.The mechanical configuration adopted here does not require continuous motor currents for posture holding. For motor drives, in fact, a fewheat sink plates adhered on the carbon frame have been proved to be enough for the thermal saturation.

As discussed before, the light unit is the most heat-generating part in the developed system. The result of thermal rating is shown in Fig.8,where the surface temperature has been measured for 3 hours. Under the condition of 25degree room temperature with no winds, the most heated portionwas saturated around 53degree, while sufficient brightness is obtained and the camera inside the heated housing has been confirmed to operate correctly. The successful functioning of the heat-source decentralization, the LED current regulationand the heat dissipation designhas been verified.

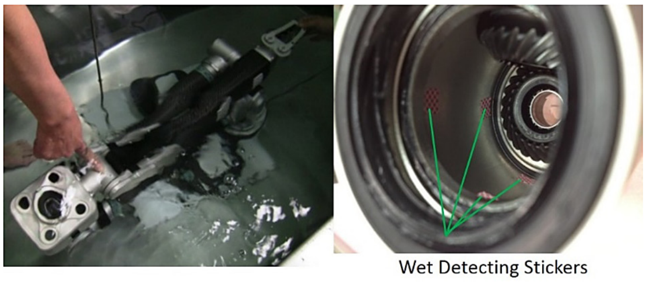

Figure 7. *Water proof testing*

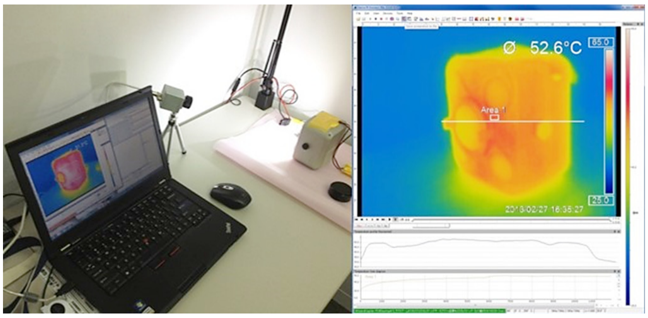

Figure 8. *Thermal dissipation evaluation*

4.3 Slip torqueverification

The function of the torque limiter is evaluated by a testing set shown in Fig.9. The 1st link side of the pitch joint is fixed on a table, and a dummy 2nd link is attached to the opposite side of the joint. A push pull gauge is used to measure forces acting on the dummy 2nd link and starting a slip at embedded torque limiter, and slip torques were measured multiple times.

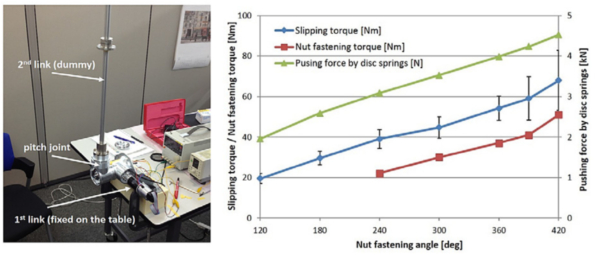

Figure 9. *Torque limiter testing set (left) and slip torque evaluation result (right)*

The results of the experiment are also summarized in Fig.9. As shown, slip torques increase as the nut fastening angle increases. Fastening torques of the nut and pushing force by disc springs are approximately proportional to the nut fastening angle. The result also shows that variability of slip torques grows wider as the nut fastening angle becomes large. These results indicate that we are able to adjust slip torques of joints according to intended tasks within the effective range of the disc spring deflection. In experiments of the camera arm joint, it was verified that the slip torque was able to be easily and appropriately adjusted by the nut fastening angle, which is used at the collision protection mechanism to gain the effective frictional dissipation of impulse energy.

4.4 Power consumptionevaluation

The reduction of power consumptions is essential not only for disaster response robots, but also for any moving robots, which have to inevitably equip their own body with energy source. Fig. 10 shows a typical remote operation example of collecting samples, where picturesof the camera view and the electrical power supply are imposed. Note that the external power supply is used here only for presentation purpose, and 30V similar to the battery voltage mounted in the crawler robot (28.8V nominal, 24Ah capacity) is supplied.For the developed camera arm, the necessary operation current at the stationary state of the armhas been 1.3A, and 1.9A has been required if the light unit is turned on. In the time that twopitch joints are driven simultaneouslyin the sampling operation, the current supply in total has been around 3 Aunder 30V supply. It is verified that the power consumption is adequately reduced for resting state to prolong the limited power source of the battery capacity.

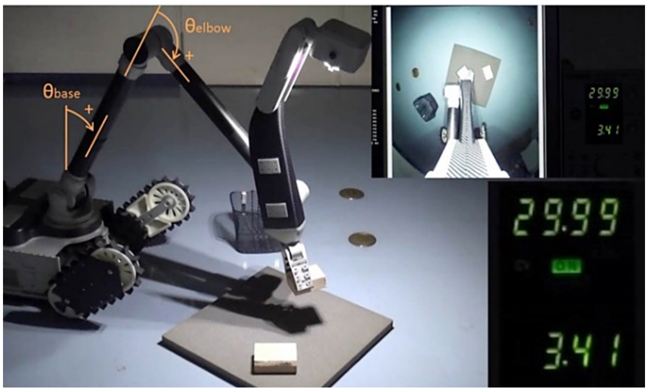

Figure 10. *Sampling operation*

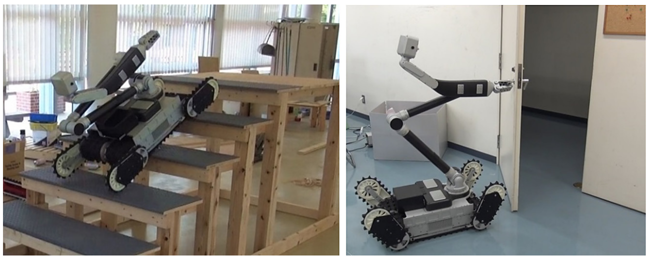

Figure 11. *Stair climbing and door opening*

4.5 Gravity center verification: stairsclimbing

The robot climbing the stair with the developed camera arm of around 20 kg on its body is shown in Fig. 11. As promised, by folding the arm compactly, the robot could go up without the loss of the gravity balance and make a point-turn motion at the narrow space of the stair case landing. Note that the crawler robot can be also remotely operated by this camera position. The highest location of the camera can reach beyond 2 m from the floor. The visual inspection at overhead positions, such as ducting pipes arranged at ceiling, can be performed by the robot at resting state.

4.6 Remote operability verification: door opening

In order to evaluate the remote operability, door opening operationwasperformed as shown in Fig. 11 (see [TODA 2014] for its sequential pictures and detailed description). The task sequence, consisting of grasping the knob, opening the door and passing through it, was achieved by the 3rd trial, and its elapsed time was 4 minutes 20 seconds. By remotely switching the yaw joint local control as active and passive according to the task progress, the difficulty in the doorknob pulling could be greatly reduced. Another essential factor for the successful operation was that the operator stress against the mechanical damagedue to collisions between the door and the gripper, could be alleviated by the properly configured collision protection mechanism. It was shown that the developed remote control system is capable of manipulating the door and passing through it.

There were mainly two reasons, where we had to retry the door opening task. First, it was hard to recognize the depth distance near the gripping point through the camera image. Second, there was fundamental difficulty to simultaneously control two multiple degrees of freedom systems, i.e. the crawler robot and the camera arm systems. For the distance recognition difficulty, simply we need additional view of the gripping point from different direction by installing secondary camera. For the second difficulty, it is required to develop an interface that can easily operate combined motions of multiple systems.

5. Conclusion

To enhance information-gathering ability of disaster response robots, a camera arm system is focused in this paper. From practical view points, functional requirements are discussed and their space-effective designs are presented. In particular, the necessary specifications of the systemand the mechanical structure for real-world missions arefully discussed. The first prototype of the camera arm system together with the crawler type remote operation robot, SAKURA II, are developed. Through evaluation experiments including several remote operation examples, it is verified that mechanically the pre-specified target performance is obtained on this prototype model. For the operation software, however, it is found that further improvements are required. As future works, in addition to efforts on hardware optimization, studies on software interface architectures allowing us stress-free operations are continued.

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